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Review on Agroforestry Systems of Indian Eastern Himalayas: Potential Role in Carbon Sequestration and Ecosystem Services

Sivaranjani Subramanian[1], Kajoli Begum[2], Wishfully Mylliemngap*[3], Sajitha Siril[4]

[1]G.B. Pant National Institute of Himalayan Environment, North-East Regional Centre, Itanagar, Arunachal Pradesh, India. Email: ranjani.agri@gmail.com | ORCID: https://orcid.org/0000-0002-0955-496

[2]G.B. Pant National Institute of Himalayan Environment, North-East Regional Centre, Itanagar, Arunachal Pradesh, India. Email: kajolikhan93@gmail.com | ORCID: https://orcid.org/0009-0000-6367-5919

[3]G.B. Pant National Institute of Himalayan Environment, North-East Regional Centre, Itanagar, Arunachal Pradesh, India. Email: wishm2015@gmail.com | ORCID: https://orcid.org/0000-0002-9232-7793

[4]College of Forestry, Kerala Agricultural University, KAU PO, Vellanikkara- 680656, Thrissur, Kerala, India. Email: sajithasirilkau@gmail.com | ORCID: https://orcid.org/0000-0002-8071-0007

**Corresponding author*

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Abstract

Agroforestry has been recognized by the Intergovernmental Panel on Climate Change (IPCC) as important for reducing soil erosion and carbon sequestration. The Indian Eastern Himalayan region is very diverse in terms of agroforestry systems varying in species composition and management practices according to agro-climatic zones as well as inherent traditional knowledge of the practising communities. This land use system forms an important part of the traditional agricultural practices of Indigenous communities of this region by supporting their livelihood and also deeply embedded in their socio-cultural traditions. The present review is an attempt to appraise the different agroforestry systems of the eastern Himalayan region of India, with a particular focus on their role in carbon sequestration and the provision of ecosystem services. Analysis of the literature revealed the multifarious types of ecosystem services that can be derived from this land use system ranging from provisioning, regulating and cultural services. Moreover, the potential for carbon sequestration was reported by several researchers and was found to vary concerning species composition and type of management. Despite its importance, agroforestry systems also face several challenges due to various factors including lack of quality planting material, market linkages, knowledge gap, and policy complications as well as the impacts of climate change. In conclusion, we highlighted several opportunities for sustainable agroforestry practices by promoting them as biodiversity conservation models, encouraging participation of agroforestry practitioners in carbon credit markets, linking farmers with agricultural extension services and integrating communities' traditional knowledge with scientific innovation for improved seed, effective soil and water management, and sustainable harvesting, value addition and marketing of agroforestry products.

Keywords

Climate change; Traditional knowledge; Carbon; North-east India; Indigenous communities

1. Introduction

Agroforestry, the practice that merges tree components with crops and/or livestock (Nair *et al.,* 2021), has been widely accepted by international organizations such as FAO (Food and Agricultural Organization), IPCC (Intergovernmental Panel on Climate Change) and CIFOR (Centre for

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International Forestry Research), especially during this era of unprecedented climatic extremes and food security concerns. Since trees are the principal components of agroforestry systems, they play a crucial role in carbon sequestration in biomass and soil and contribute to microclimate amelioration. In addition, agroforestry systems conserve biodiversity, enhance soil fertility and improve water quality. Besides the ecological roles, agroforestry systems also ensure economic benefits, including food, fodder, fuel, manure, and social benefits, such as recreation and mental well-being.

India, the first country to formulate a National Agroforestry Policy in 2014 (Chavan *et al.*, 2015), harbours various agroforestry systems and practices, varying from region to region, and the plant composition changes even between nearby localities. Agroforestry systems were broadly categorized into agri-silvicultural (crop and trees), silvi-pastoral (trees and livestock), and agri-silvopastural (crop, tree, and livestock). Other prominent agroforestry systems in India include windbreaks, shelterbelts, alley cropping and home gardens (Sekhar *et al.,* 2024).

The Indian part of the Eastern Himalayas consists of northeastern states Arunachal Pradesh, Manipur, Mizoram, Sikkim, Tripura, and Meghalaya, hill districts of Assam and the Darjeeling District in West Bengal (Nandy *et al.*, 2006). The primary land use of hill farmers in northeast India is agriculture. Traditional agricultural practices such as shifting cultivation have been criticized by many as they cause the emission of greenhouse gases by burning forest residues and most importantly shortening of the fallow period causes significant soil degradation and degradation of forest lands. Agroforestry emerged as an alternative to such land use practices and has been recommended as a suitable strategy for sustainable land management in northeast India (Nath *et al.,* 2020). The prominent agroforestry systems in northeast India include agri-silviculture, agri-horti-silvi-pisciculture, agri-horti-silviculture and horti-silvi-pastoral systems (Deb, 2020). These agroforestry systems have been documented for their role in maintaining biodiversity, conserving threatened species, enhancing soil quality, sequestering carbon, increasing crop yield, improving living standards and providing aesthetic values (Ahirwal *et al.,* 2022; Dutta *et al.,* 2023; Sharma *et al.,* 2007).

Specific agroforestry practices in northeast India include home gardens, Parkia-based agroforestry systems, areca-based agroforestry systems, oil palm-based agroforestry systems and Borrasus-based agroforestry systems, tea gardens and large cardamom-based agroforestry systems (Jeeceelee and Sahoo, 2022; Kalita *et al.,* 2022; Sharma *et al.,* 2007; Thangjam *et al.,* 2023; Yashmita-Ulman 2021;). These agroforestry systems are crucial for enhancing ecosystem services, achieving land degradation neutrality and contributing to the United Nations Sustainable Development Goals (Ahirwal *et al.,* 2022). However, studies have yet to comprehensively document different agroforestry systems of the eastern Himalayas, whereas studies are done on the western Himalayas (Sharma *et al.,* 2022). Hence, this study is an attempt to appraise the agroforestry systems practiced in the eastern Himalayan region of India, with a particular focus on their role in terms of economic, ecological, and social benefits.

2. Agroforestry Systems of Indian Eastern Himalayas

2.1. Diversity of Agroforestry Systems

The Eastern Himalaya region, particularly in Northeast India, is a unique

ecological zone characterized by its rich biodiversity, varied topography, and distinct climatic conditions. The indigenous communities in this region have developed traditional agroforestry systems that are closely aligned with the local environment, cultural practices, and socio-economic needs. Indigenous agroecosystems are highly site-specific and differ from place to place, as they have evolved along divergent lines (Chandra *et al.,* 2011). Some of the widely practised indigenous systems followed in this region are discussed in detail in the following subheads.

2.1.1. Agri-silvicultural System

In agri-silviculture, trees and crops are integrated and grown together on the same plot, either simultaneously (e.g., hedgerow intercropping) or sequentially (e.g., improved fallows). This system currently covers approximately 8.68 million hectares in India (Nath *et al.,* 2021a). Historically, this practice has been adapted to local agro-climatic conditions, allowing for diverse cultivation of staple grains, rhizomatous crops, and cash crops like pineapple, coffee, and tea (Kumar *et al.,* 2023). Key tree species such as *Alnus nepalensis* and *Schima wallichii* support sustainable land management and community development (Pandey *et al.,* 2022). Nagaland exemplifies successful agri-silviculture with its reliance on Alder, supporting high-value crops like cardamom (*Elettaria cardamomum*) and improving farmer incomes (Kehie *et al.,* 2017). Shifting (*Jhum*) cultivation remains essential in Mizoram's traditional farming (Singh, 2019). In the Barak Valley of Assam, pineapple and piper-based agroforestry systems are gaining traction, enhancing farming resilience (Chanu *et al.,* 2023). The Brahmaputra Valley features diverse systems, including Morus and castor-based systems and tea plantations, integrated with multipurpose trees (Ulman *et al.,* 2022).

2.1.2. Agro-silvopastoral Systems

Agri-silvopastoralism involves the integration of crops, pastures, livestock, and woody perennials within a singular agricultural system. The agri-silvopastoral system is characterized by agroforestry practices such as home gardens with animals, and fodder trees/shrubs on farmlands. Different components such as trees/shrubs, food and cash crops vegetables, as well as livestock make up this agroforestry system. It played various functions including provision of food, fuelwood, fodder, finance, soil fertility improvement, erosion control, wind control, climate moderation and many more (Tsufac *et al.,* 2021). Agri-silvopastoral systems cover an estimated land area of 5.58 million hectares (Dagar *et al.,* 2013) in India. Home gardens, beekeeping, aquaculture, and backyard gardens with animals are common practices in northeastern states like Assam and Tripura and are excellent examples of agri-silvopastoral systems (Das and Das, 2005). In Arunachal Pradesh, the Apatani system exemplifies this synergy, where rice is cultivated alongside fish culture in paddy fields, enhancing both productivity and biodiversity. Similarly, in the Jaintia Hills of Meghalaya, the Bun system combines rice cultivation with aquaculture, promoting sustainable land use while improving food security (Giri *et al.,* 2020).

Nagaland's Zabo system further highlights the region's innovative practices, integrating forest conservation with agriculture and livestock rearing. Here, farmers use rainfall runoff from hilltops to irrigate fields, ensuring crop resilience and enhancing livestock health (Giri *et al.,* 2020). In Assam, the cultivation of indigenous trees like Morus and Castor supports silkworm rearing, with home

gardens serving as multifunctional spaces for both crops and livestock (Ulman *et al.,* 2022). These diverse agri-silvopastoral systems illustrate the region's adaptive strategies for sustainable development, reflecting a deep connection between local cultures and their environment.

2.1.3. Silvi-pastoral Systems

In silvi-pastoralism, trees are integrated with pastures and livestock husbandry where trees may be planted or retained in a grazing system to supplement animal feed or to provide proteins during the dry season when grass is scarce and nutritive content is poor. They include a diversity of systems, either intensive systems, for example, fodder banks, intensive feed gardens, or extensively managed systems for example open grazing. There are currently an estimated 2.42 million hectares of silvi-pastoral systems in India (Nath *et al.,* 2021a). The main components of silvi-pastoral systems are the production of food, the provision of fodder, the production of fuelwood, the provision of shade, and the control of temperature (Tsufac *et al.* 2021).

2.2. Case Studies from the Indian Eastern Himalayan Region

The Eastern Himalayan region of India is characterized by a diverse array of unique agroforestry systems that have developed in response to the region's varied ecological and climatic challenges. These case studies highlight the innovative practices adopted by local communities, showcasing their ability to harmonize agriculture with environmental conservation. From the raised beds of Meghalaya's Bun system to the multi-crop agroforestry systems in Sikkim, the agricultural methods discussed here emphasize the importance of biodiversity, sustainability, and traditional knowledge. Each case study illustrates how farmers are balancing productivity with ecological health, offering valuable insights into sustainable farming practices that could be emulated elsewhere.

2.2.1. Bun System of Cultivation in Meghalaya

The *Bun* system of cultivation, endemic to Meghalaya, represents a unique agricultural methodology tailored to the region's challenging topography and climatic conditions. This practice involves constructing a series of raised beds along hillslopes, facilitating the cultivation of various crops while addressing soil and moisture management issues. Typically, the raised beds measure between 75 and 150 cm in width, accompanied by sunken furrows ranging from 50 to 100 cm. The height of these beds varies between 15 and 45 cm, influenced by soil depth and moisture availability. Farmers utilize locally sourced organic materials—such as crop residues, tree leaves, and other phyto-mass — to enrich the soil. This biomass is either decomposed in situ or incinerated, thereby enhancing the nutrient profile of the soil. As a modified form of shifting cultivation, the *Bun* system allows fields to be cultivated for a limited period, generally two years, before undergoing a fallow phase for soil recovery. This practice is particularly advantageous on mild to steep slopes, optimizing drainage during intense rainfall, which is crucial for crop health.

Crops cultivated through this method include maize, ginger, turmeric, potatoes, and various vegetables. Notably, intercropping practices are employed in areas such as the Jaintia Hills, where maize serves as a support for climbing legumes like French beans and soybeans, thus improving agricultural productivity. However, this system is not without its challenges. The configuration of raised

beds can lead to significant soil erosion, prompting farmers to adopt innovative measures such as vegetative barriers. These barriers are instrumental in curbing runoff and enhancing soil conservation, thereby ensuring the sustainability of this traditional practice. In conclusion, the *Bun* system of cultivation embodies a sophisticated blend of traditional knowledge and environmental adaptation, playing a crucial role in the agricultural landscape of Meghalaya (Das *et al.* 2012).

2.2.2. Large Cardamom-based Traditional Agroforestry Systems of Sikkim

In Sikkim, the large cardamom-based agroforestry system is a purely traditional land use adaptation in the fragile, inaccessible, vulnerable and marginal mountain slopes of the eastern Himalayan region (Sharma *et al.* 2007). This traditional adaptive management system has been potential livelihood support to the smallholders, a means to biodiversity conservation, environmental services ecological health and social and economic well-being of the people. Large cardamom (*Amomum subulatum*) is a perennial cash crop grown under the Himalayan alder (*Alnus nepalensis*) or mixed forest tree species. The shade-loving plant requires high moisture and is usually cultivated in areas where mean annual rainfall varies between 1500-3500 mm. Common shade trees for the agroforestry are *Schima wallichii*, *Engelhardtia acerifolia, Eurya acuminata, Leucosceptrum canum, Maesa chisia, Symplocos theifolia, Ficus nemoralis, Ficus hookeri, Nyssa sessiliflora, Osbeckia paniculata, Viburnum cordifolium, Litsaea polyantha, Macaranga pustulata*, and *Alnus nepalensis*. Hence, the large cardamom agroforestry practice also supports the conservation of tree biodiversity in the region (Sharma *et al.* 2009). The plantation areas of this crop in other Indian Himalayan regions comprise 550 ha spread over five states. Nagaland (35 ha), Mizoram (35 ha), Meghalaya (10 ha), Manipur and the central Indian Himalayan state Uttarakhand (41 ha) covering a total of 34,252 ha in India (Srinivasa, 2006).

2.2.3. Banana-Based Agroforestry in Mizoram

Banana (*Musa paradisiaca*) is a prominent crop in Mizoram, deeply embedded in the region's agricultural landscape and cultural ethos. In villages such as Khumtung and Baktwang, residents associate banana cultivation with protection from natural disasters and enhanced prosperity, reflecting a strong cultural reverence for this crop (Singh *et al.,* 2014). In the context of agroforestry, bananas are not cultivated in isolation; they are strategically inter-planted with a variety of annual crops and leafy vegetables, notably Lai Pata (*Brassica juncea*). This polyculture approach not only optimizes land use but also fosters ecological diversity, improving both yields and resilience. Recent trends indicate an expansion into fruit cultivation, with lemons (*Citrus limon*) and oranges (*Citrus sinensis*) increasingly integrated into these systems. This diversification enhances economic stability for farmers, allowing them to buffer against market volatility and crop failures (Singh *et al.,* 2014). Furthermore, banana plants significantly contribute to soil health by adding organic matter, which enriches soil fertility and mitigates erosion — a crucial benefit given Mizoram's hilly terrain. Thus, banana-based agroforestry emerges as a sustainable agricultural practice that harmonizes cultural beliefs with ecological sustainability and economic viability.

2.2.4. Alder-based Farming System of Nagaland

Alnus nepalensis (D. Don, 1825) commonly known as alder is a non-leguminous nitrogen-fixing tree that can grow up to 30 m tall. Recognized for its

multi-functionality, alder provides timber, fuel wood, and fodder, while also enhancing soil health, and supporting biodiversity by offering habitat for diverse plant and animal species, thereby improving the resilience of farming systems. Tribal farmers in Nagaland, such as those from Angami, Chakesang, and Yimchunger communities, have effectively integrated this species into their agricultural practices for over two centuries (Gokhle *et al.,* 1985; Singh, 1992). In these agroforestry systems, alder is planted on sloped lands, where its rapid growth within 6 to 10 years allows farmers to employ a technique known as pollarding. This process involves cutting back the trees annually during the dry season, with the ash from the burnt leaves enriching the soil for subsequent crop cultivation (Das *et al.,* 2012). In villages such as Khonoma, the alder-based system exemplifies an adaptive and sustainable land-use strategy, allowing farmers to harvest crops in a 1:1 cropping-to-fallow ratio, significantly improving productivity compared to traditional *jhum* cultivation, which often follows a 1:4 ratio (Das *et al.,* 2012). Farmers cultivate up to 57 different edible crops, including primary staples like rice, maize, and potatoes, alongside various secondary crops during the initial two years of cropping (Das *et al.,* 2012). This biodiversity not only enhances food security but also promotes ecological resilience.

The symbiotic relationship between alder and the nitrogen-fixing Actinomycete *Frankia* allows the tree to enrich soil through nitrogen fixation, making it valuable for restoring degraded *jhum* lands (Baker and Schwintzer, 1990; Benson and Silvester, 1993). Alders develop root nodules that create a suitable environment for *Frankia*, similar to the relationship between legumes and *Rhizobium*. This process varies by tree density, yielding 48.3 kg/ha to 184.8 kg/ha of fixed nitrogen, supplemented by litter that adds essential nutrients like phosphorus, potassium, and calcium (Sharma and Prasad, 1994; Sharma and Singh, 1994). Integrating alder into farming in Northeast India exemplifies a holistic agroforestry approach that combines traditional knowledge with sustainable land management, enhancing productivity while preserving environmental health. Continued research and community engagement are essential for refining these practices and ensuring their long-term viability.

2.2.5. Apatani Fish-Cum-Paddy Cultivation in Ziro Valley, Arunachal Pradesh

Paddy-cum-fish cultivation is an Indigenous organized farming method of the Apatani tribe of Arunachal Pradesh locally known as *Aji-ngyii*: '*Aji*' meaning cultivation and '*ngyii*' meaning fish. The practice was considered to be one of the most productive and efficient agricultural systems in the region (Nimachow *et al.,* 2010). The practice involves the integration of wet-rice cultivation with Indigenous millet (*Eleusine coracana*) and fish rearing on the same field. While paddy is grown on the field, millet is grown along the bunds surrounding the rice fields. *Houttuynia cordata*, an edible herb growing wild on the lower sides of bunds is not weeded out, but retained, to act as a soil binder to further strengthen the bunds. About 16 local varieties of rice and 4 millet varieties, classified into early- and late-maturing varieties, have been reported to be grown in wet-rice farming systems (Dollo *et al.,* 2009; Kala, 2008). Small pits are prepared in each terrace plot for keeping fish fingerlings, and the fields are filled with water during monsoon season different fish varieties are reared on the standing water of the rice fields maintained at about 5 to 10 cm and fishes can move all over the rice fields. During the drier period when water is scarce, water remains only in the trenches where fishes retreat and continue to grow. Manuring of paddy fields also acts as

a nutrition source for the fish, as such there is no requirement for additional fish feeds. In this system, both paddy and fish are produced together by proper management of rainwater (Rai, 2005). Different species of Indigenous fishes such as *Channa* spp., *Puntius* spp., *Schizothorax* spp., els), *Nemaucheilus dookensis*, dorikona (*Esomus danricus*) or weed fish were found naturally occurring in the stream draining the paddy fields are raised in the system. Other commercial species were introduced by the state government such as common carp (*Cyprinus caprio*), silver carp (*Hypophthalmichthyes molitrix*), grass carp (*Ctenopharyngodon idella*), *Labeo gonius* and *Barbonymus gonionotus*). However, the common carp remains the most-reared species and the success rate is also found to be higher than the other varieties of fish (Nimachow *et al.,* 2010). The productivity of the Apatani paddy-cum-fish farming system was reported to be 400–500 kg/ha which is 3–4 times of average yield of Arunachal Pradesh (Rai, 2005).

2.2.6. Rice-Based Farming System in Tripura

Rice-based farming systems (RBFS) in Tripura, India, are deeply rooted in traditional practices that significantly contribute to resource conservation and food security. RBFS is an enduring agricultural practice that has evolved over centuries, deeply rooted in the region's cultural and ecological contexts. This system is characterized by its adaptability to various terrains, including upland, medium upland, and lowland rice fields. These systems integrate various agricultural components, including water harvesting, livestock management, and indigenous fish farming, which collectively enhance the resilience of local communities. (Das *et al.,* 2015). In this multifaceted system, the utilization of animal manure as organic fertilizer plays a crucial role in enriching soil health, promoting sustainability, and minimizing chemical inputs. During the monsoon season, farmers cultivate an array of vegetables like colocasia (elephant ear plant), okra or lady's finger, and brinjal (eggplant), while winter months see the growth of crops such as potatoes and sweet gourd. Additionally, the cultivation of fruit trees, including banana, guava, and coconut, adds further diversity and resilience to the system (Yadav *et al.,* 2013). To address the challenges posed by limited landholdings — typically less than one hectare — farmers have innovated by implementing water harvesting techniques. Ponds not only facilitate irrigation but also support aquaculture, contributing to an average fish productivity of 0.75 to 1.2 tons per hectare (Das *et al.,* 2015). Integrating livestock into the RBFS enhances the economic stability of farming families while improving overall productivity. As food security concerns grow, it is essential to invest in agricultural technologies and develop high-yield varieties to ensure the sustainability and effectiveness of this vital farming system in Tripura (Yadav *et al.,* 2013).

3. Role of Agroforestry in Carbon Sequestration

Agroforestry enhances soil carbon sequestration through increased organic matter inputs from leaf litter, root turnover, and root exudates. The presence of trees helps improve soil structure, reduce erosion, and increase water retention, all of which contribute to the stabilization of soil organic carbon. In addition, deep-rooted trees access and cycle nutrients from deeper soil layers, further enhancing soil fertility and carbon storage. Jose (2009) reported that agroforestry practices can enhance soil carbon stocks by up to 34% compared to traditional monoculture systems. In addition to sequestering carbon, agroforestry contributes to the

reduction of greenhouse gas emissions by decreasing the need for chemical fertilizers, which are significant sources of nitrous oxide (N_2O), a potent greenhouse gas. Through biological nitrogen fixation by leguminous trees and the improved nutrient cycling associated with agroforestry systems, the demand for synthetic fertilizers can be significantly reduced. This contributes to lower overall emissions from agricultural production.

The integration of trees in agricultural systems also has the potential to offset carbon emissions from deforestation and land-use change. In many parts of the world, agroforestry is used as a buffer against deforestation, maintaining ecosystem services such as biodiversity conservation and watershed protection. Studies have shown that agroforestry can significantly reduce deforestation rates by providing alternative livelihoods and decreasing pressure on forest ecosystems (Zomer *et al.,* 2014).

3.1. Carbon Sequestration Potential of Agroforestry Systems as Carbon Sinks

Agroforestry systems in the northeastern states consist of a variety of practices such as home gardens, shifting cultivation (*jhum*), bamboo-based farming, and silvi-pastoral systems. These systems are well-suited to the region's hilly terrain and can significantly contribute to carbon sequestration. Studies have shown that agroforestry systems in tropical and subtropical regions, like those in northeastern India, can sequester up to 25-50 tons of carbon per hectare, depending on the type of trees, soil conditions, and management practices (Nair *et al.,* 2009). The mix of trees, crops, and livestock in these systems increases the amount of carbon stored in both aboveground biomass and soils. Bamboo-based agroforestry systems, widely practised in the northeastern states, hold immense potential for carbon sequestration. Bamboo grows rapidly and has a high capacity to store carbon both in its biomass and in the soil. Studies show that bamboo can sequester up to 12 tons of carbon per hectare annually (Solomon *et al.,* 2020), making it a significant contributor to carbon storage in agroforestry systems. The steep slopes and heavy rainfall in the region lead to significant soil erosion, but tree-based systems help stabilize soils, reduce runoff, and enhance water retention. This improves soil organic carbon stocks, further contributing to carbon sequestration (Limboo, 2022).

3.2. Comparative Study on How Carbon Sequestration Capacity Differs Due to Species Selection and Practices

3.2.1 Species Selection and Carbon Sequestration Capacity

In the North Eastern states, the choice of tree species for agroforestry systems significantly impacts carbon sequestration. Tree species native to the region, as well as those introduced for agroforestry purposes, exhibit different growth rates, biomass accumulation patterns, and carbon storage capacities. Fast-growing species such as *Bambusa tulda* (Bamboo) and *Alnus nepalensis* (Alder) are widely used in traditional agroforestry systems due to their rapid growth and ability to sequester carbon quickly. *Bambusa tulda*, known for its ability to grow rapidly and accumulate large amounts of biomass, is an effective short-term carbon sink. Bamboo-based systems have been reported to sequester 12-15 tons of carbon per hectare annually, depending on site conditions and management practices (Nath *et al.,* 2012). *Alnus nepalensis* also contributes to both aboveground biomass and belowground carbon storage through its ability to fix nitrogen, which enhances soil

fertility and organic matter accumulation (Limboo, 2022).

In contrast, slow-growing, high-wood-density species like *Shorea robusta* (Sal) and *Castanopsis indica* (Oak) found in Arunachal Pradesh and other parts of the region are excellent long-term carbon sinks due to their dense wood and longer lifespans, enabling them to store carbon over extended periods. While slow-growing species take longer to accumulate biomass, their role in long-term carbon sequestration is critical for maintaining forest carbon stocks over time (Kaul *et al.,* 2010). Leguminous trees like *Albizia lebbeck* and *Parkia roxburghii* are also commonly used in agroforestry systems in the region, particularly in Assam and Meghalaya. These species enhance carbon sequestration not only through their biomass but also by improving soil organic carbon through nitrogen fixation. The addition of nitrogen-fixing species improves soil structure and increases the capacity for carbon storage in soils, making them effective components of agroforestry systems aimed at increasing both aboveground and belowground carbon sequestration (Nair *et al.,* 2009).

3.2.2 Agroforestry Practices and Carbon Sequestration

The traditional agricultural systems of the Indian Eastern Himalayan states, including shifting cultivation (*Jhum*), have both positive and negative impacts on carbon dynamics depending on the frequency of cycles and the incorporation of trees in the landscape. Transitioning from shifting cultivation to more sustainable agroforestry systems, such as tree-based farming, can enhance long-term carbon storage in both biomass and soils. Bamboo-based agroforestry systems are particularly effective in areas prone to soil erosion, such as the hill slopes of Assam and Meghalaya. The extensive root system of bamboo helps in stabilizing the soil and increases carbon sequestration in deeper soil layers. Silvi-pastoral systems, which integrate trees and livestock grazing, offer the dual benefits of enhancing carbon sequestration while supporting livelihoods through livestock production. Trees in silvi-pastoral systems provide shade and increase soil fertility, while also sequestering carbon in their biomass. A study in Assam demonstrated that silvi-pastoral systems could sequester up to 35 tons of carbon per hectare, compared to 15-20 tons in conventional grazing systems (Mutuo *et al.,* 2015). The inclusion of nitrogen-fixing trees further improves soil carbon storage, making these systems more resilient to climate change.

In the hilly areas of Arunachal Pradesh, Nagaland, and Mizoram, agroforestry systems on sloping lands have emerged as an alternative to shifting cultivation. By integrating deep-rooted trees with crops, these systems enhance soil carbon sequestration while preventing soil erosion. For example, systems that incorporate deep-rooted species like *Ficus roxburghii* (fig) and *Cinnamomum tamala* (Indian Bay Leaf) improve soil structure and sequester carbon in deeper soil layers, where it is less likely to be lost due to erosion (Limboo, 2022).

The adoption of sustainable agroforestry practices, such as silvi-pastoral systems and mixed-species agroforestry on sloping lands, has proven to significantly enhance carbon sequestration in the region. These practices not only improve carbon storage in both biomass and soils but also provide additional ecosystem services, such as soil conservation, water retention, and biodiversity enhancement. Fast-growing species like *Bambusa tulda* provide rapid carbon capture, while slow-growing species like *Shorea robusta* ensure long-term carbon storage. Agroforestry practices that minimize soil disturbance, promote species diversity, and incorporate nitrogen-fixing species can further enhance carbon

sequestration in both biomass and soils. As the region seeks to mitigate climate change, these agroforestry systems offer sustainable solutions for carbon sequestration and environmental resilience.

4. Ecosystem Services Provided by Agroforestry Systems

Ecosystem services are 'the benefits people obtain from ecosystems' (MEA, 2005). Ecosystem services consist of tangible and non-tangible goods and services that different ecosystems provide which are essential for human life and wellbeing. For example, forest ecosystems provide tangible goods like wood and other non-wood forest products for human use and the economy, as well as intangible services like climate regulation, preventing soil erosion, air purification and other services. Several researches have shown that agroforestry systems are beneficial by providing multiple ecosystem services such as soil erosion control, ecosystem functional processes that determine soil health and, providing income for farmers and contribute to environmental sustainability (Duffy *et al.,* 2021; Iñamagua-Uyaguari *et al*., 2023; Maitra *et al.,* 2023).

For this review, we followed the Common International Classification of Ecosystem Services (CICES) developed by the European Environment Agency (EEA). According to CICES, the provisioning, cultural and regulating services as provided by MEA were retained while the supporting services were recognized as underlying functions that characterize the ecosystems. The latest available version of CICES version v5.1 (EEA, 2016) was used to enumerate the ecosystem services provided by agroforestry systems.

4.1. Provisioning Ecosystem Services

Provisioning ES comprises 'all nutritional, non-nutritional material and energetic outputs from living systems as well as abiotic outputs (including water)'. For example, food, fodder, fibre, genetic material derived from cultivated and wild plants, animals and microorganisms. A review of different agroforestry systems of the Indian eastern Himalayas reveals the immense diversity of provisioning services characteristic to the regions and needs of the practicing community. The provisioning services that can be obtained from these systems include those produced by cultivated species such as food crops, timber and cash crops essential for human sustenance and economic benefit. Other provisioning ES include semi-domesticated and wild plants used for supplementary food as well as medicine, fibre, fodder, raw materials for construction and handicrafts. In particular, the traditional pisciculture-based AFS of Assam and wetland-based AFS of Tripura provide terrestrial as well as aquatic-based provisioning services in the form of fish and aquatic plants used as food sources. Specifically, tea garden-based, Large cardamom, Piper-based and pineapple-based AFS primarily focus on specific crops as major provisioning ES, viz., tea leaves and large cardamom spice, Piper betel leaves and pineapple fruit, respectively which are the main cash crops providing economic benefits to the human communities. Other ecosystem services obtained from these systems are those provided by associated crops such as multipurpose plant species for timber, fodder, fuelwood, fibre, fruits and other products for human necessities. On the other hand, such as home gardens traditional AFS are practiced mainly for meeting household necessities and not for commercial benefits (Table 1).

4.2. Regulation and Maintenance Services

All the ways in which living organisms can mediate or moderate the ambient environment that affects human health, safety or comfort, together with abiotic equivalents. For example, seed dispersal, erosion control, mediation of toxic wastes by living organisms, and weed control. The most common regulation and maintenance ES of the agroforestry systems of the Indian Eastern Himalayas include the provision of shade and regulation of the microenvironment, preventing soil erosion, nutrient cycling, carbon storage and water resource management and air purification. Specifically, the Alnus-cardamom agroforestry system of Sikkim and the Alder-based shifting cultivation of Nagaland utilized the nitrogen-fixing tree species, *Alnus nepalensis*, which enhances soil nitrogen availability and improved soil fertility (Sharma *et al.*, 2007). Large cardamom AFS have also been reported to provide habitat to a variety of pollinators. Waste management is exhibited by the pisciculture-based AFS of Assam and some horti-silvi-pastoral systems of Arunachal Pradesh. In the former practice, the plant waste/litter generated are converted into fish feeds while in the latter the animal waste is used as manure for growing trees and crops thus enabling efficient management and recycling of waste materials within the system. In the Alder-based and Macaranga-based *Jhum* cultivation systems of Nagaland, the associated tree species aided in the rejuvenation of *jhum* fallows and maintenance of soil moisture through leaf litter mulch. Lastly, since most of the AFS was traditionally practiced by Indigenous communities and consists of locally important species, these systems can potentially serve in conserving native biodiversity and in some cases rare and endemic species of flora and fauna (Singh and Gupta, 2007; Tynsong and Tiwari, 2010) (Table 1).

4.3. Cultural Services

All the non-material, and normally non-rival and non-consumptive, outputs of ecosystems (biotic and abiotic) that affect physical and mental states of people. This category includes the characteristics of the ecosystem that enable education and training, aesthetic experience, spiritual and religious value, entertainment, etc. The Indian Eastern Himalayas boast of its rich cultural and ethnic diversity which is reflected in the existence of a variety of agroforestry practices each unique to a certain agro-climatic zone or resident ethnic community (Table 1). Consequently, the traditional AFS of the region is a rich storehouse of traditional ecological knowledge. This knowledge offers a great opportunity for research and education. Certain Agroforestry systems such as Macaranga-based *jhum* cultivation have their associated folklore regarding the macaranga tree (*Macaranga tanarius*) (Changkija *et al.,* 2023) thus emphasizing its socio-cultural importance. Management of agroforestry systems often involves collective responsibility by the community which strengthens society ties and traditional institutions. Large cardamom-based AFS of Sikkim provide recreational opportunities and offer cultural services that enhance the well-being of communities and society at large (Sharma *et al.* 2007). Other AFS also have tourism value which may be attributed to their aesthetic appeal, cultural heritage or simply because they offer a calm and refreshing environment for people to enjoy and relax in the lap of nature contributing to a healthy body and mind.

Table 1: Types of ecosystem services provided by some major agroforestry systems of northeast India

State	*Type of AFS*	*Key ES types*			*References*
		Provisioning	*Regulation & Maintenance*	*Cultural*	
Assam (Barak valley)	Traditional AFS- Piper based	Fuelwood, timber, cash crops	Shade trees, companion trees (for supporting piper plants)	Traditional knowledge, aesthetic value	(Reang *et al.*, 2022)
Assam (Barak valley)	Traditional AFS- Pineapple-based	Timber, cash crops	Shade trees, live fencing, soil erosion control	Traditional knowledge, aesthetic value	(Reang *et al.*, 2022)
Assam	Pisciculture-based AFS	Timber, fruit, vegetables, medicine, cash crops, fish, leaf litter as fish feeds	Regulation of microenvironment, water resource management, waste recycling	Traditional ecological knowledge, socio-cultural value	(Deb, 2020)
Assam	Tea garden AFS	Economic benefit, multipurpose trees	Shade trees, N_2 fixation, C sequestration	Culture and heritage, tourism value	(Kalita *et al.*, 2016); Magar and Kar, 2016)
Arunachal Pradesh (Ziro Valley)	Integrated bamboo + pine home-gardens	Timber, food, fuelwood, medicine, economic benefit, raw materials for housing, fencing, handicrafts, rites and rituals	Soil nutrient cycling, biomass & carbon storage, soil erosion control, weed reduction through pine needle, water resource management	The cultural heritage of the Apatani tribe, conservation education, tourism value	(Tangjang and Nair, 2016)
Arunachal Pradesh	Agri-horti-silvicultural system	Food crops, fuelwood, timber, medicine, spices	Sustain long-term productivity of the land	Traditional knowledge, socio-cultural value	(Deb, 2020)
Arunachal Pradesh	Horti-silvi-pastoral systems	Timber, construction materials, fruits, fodder, livestock and their products	Waste management, maintains soil fertility, nutrient recycling	Traditional knowledge, socio-cultural value	(Deb, 2020)
Manipur	Home Garden	Fruit and vegetable crops, medicinal, fodder, aqua-cultural, socio-cultural, ornamental plants	Maintain native plant diversity	Sociocultural functions, Aesthetic value in ornamental plants	(Singh and Gupta, 2007)
Meghalaya	Betel Leaf AFS	Timber, fuelwood, edible plants and spices, ornamentals, raw materials for tool making and handicrafts, latex	Companion trees (for betel vine support), habitat for endemic and rare flora and fauna	Socio-cultural values, traditional ecological knowledge	(Tynsong and Tiwari, 2010; Tynsong *et al.*, 2018)
Mizoram	Traditional AFS- Homegarden	Food, timber, fodder, fibre, charcoal	Shade trees, companion trees	Traditional knowledge, aesthetic value	(Reang *et al.*, 2022)

State	*Type of AFS*	*Key ES types*			*References*
		Provisioning	*Regulation & Maintenance*	*Cultural*	
		preparation, ornamental plants		through ornamental plants	
Nagaland	Alder-based *Jhum* AFS	Food crops, timber, fuelwood, charcoal making	Biological N_2 fixation through Alder (*Alnus nepalensis*) tree roots, soil erosion control, slope stabilization	Traditional ecological knowledge, Conservation value for native biodiversity, socio-cultural values	(Kehie *et al.*, 2018)
Nagaland	Macaranga-based *Jhum* AFS	Food crops, fuelwood, timber	Rejuvenation of *Jhum* fallow, improves soil fertility, companion plants, and soil moisture conservation through leaf litter	*Macaranga* species associated with local folklore, traditional ecological knowledge	(Changkija *et al.*, 2023)
Sikkim	Large cardamom AFS (Alnus-based)	Large cardamom capsules, fuel wood	Biological N_2 fixation through *Alnus* roots, soil erosion control in steep slopes, habitat for pollinators	Traditional knowledge, cultural and spiritual traditions of Indigenous communities, strengthen traditional institutions	(Sharma *et al.*, 2007)
Tripura	Wetland based AFS	food, fuelwood, timber, medicine, fodder, livestock and aquaculture	Carbon storage, water resource management	Protection of nature, education, recreational and aesthetic value	(Taran and Deb, 2019)

5. Climate Change Impacts on Agroforestry Systems

5.1. Changes in Temperature and Crop Productivity

Rising temperatures, one of the most direct consequences of climate change, are already affecting agroforestry systems globally. Higher temperatures can alter the phenology (timing of biological events) of tree species, impacting their growth cycles, flowering, and fruiting patterns. In tropical agroforestry systems, such as those found in India and sub-Saharan Africa, increased temperatures have been linked to reduced crop yields and tree growth. Studies have shown that temperature stress reduces carbon assimilation rates in trees, which can lower their carbon sequestration capacity (Albrecht and Kandji, 2003). In the context of agroforestry systems, temperature increases can also lead to mismatches between tree species and crops. For instance, a study in Kenya found that heat stress negatively impacted shade trees used in coffee agroforestry systems, resulting in reduced crop productivity and ecosystem services (Lemma and Megersa, 2021). If the trends continue, temperature increases may force farmers to shift to more heat-tolerant tree and crop species, potentially disrupting existing ecosystems and practices.

5.2. Altered Precipitation Patterns and Water Stress

Changes in precipitation patterns, particularly the increased frequency of droughts and erratic rainfall, are among the most serious threats to agroforestry systems. Many agroforestry systems depend on regular rainfall patterns for optimal tree and crop growth. In regions like South Asia, Africa, and Latin America, rainfall variability due to climate change is already disrupting the water balance in these systems, leading to water stress for both trees and crops (Marwa and Hachicha, 2024).

Drought conditions negatively affect the growth of deep-rooted trees that usually support agroforestry systems by stabilizing soils and improving soil moisture retention. For example, in semi-arid regions of India, water scarcity has been found to severely reduce the growth rates of species like *Acacia nilotica* and *Azadirachta indica*, which are commonly used in agroforestry (Soni *et al.,* 2017). Similarly, in tropical regions, where agroforestry systems heavily rely on consistent rainfall, prolonged dry spells can lower productivity and reduce biodiversity, thereby impacting the resilience of the entire system.

5.3. Increased Frequency of Extreme Weather Events

Extreme weather events, such as cyclones, floods, and wildfires, are becoming more frequent and severe as a result of climate change. These events pose significant risks to agroforestry systems by damaging trees, destroying crops, and eroding soils. In the aftermath of extreme weather events, the ability of agroforestry systems to recover can vary depending on the resilience of the species involved. A study by Krishnamurthy *et al.* (2019) documented how extreme storms and hurricanes in Central America caused extensive damage to tree-based systems, resulting in a loss of both aboveground and belowground biomass. In many cases, it took years for these systems to recover their pre-disaster carbon sequestration potential. Similar challenges have been observed in flood-prone areas of South Asia, where intense monsoon rains have led to the destruction of agroforestry systems, particularly those located on sloping lands (Poudel *et al.,* 2023).

5.4. Pests, Diseases, and Invasive Species

Extreme weather events, such as cyclones, floods, and wildfires, are becoming more frequent and severe as a result of climate change. These events pose significant risks to agroforestry systems by damaging trees, destroying crops, and eroding soils. In the aftermath of extreme weather events, the ability of agroforestry systems to recover can vary depending on the resilience of the species involved. A study by Krishnamurthy *et al.* (2019) documented how extreme storms and hurricanes in Central America caused extensive damage to tree-based systems, resulting in a loss of both aboveground and belowground biomass. In many cases, it took years for these systems to recover their pre-disaster carbon sequestration potential. Similar challenges have been observed in flood-prone areas of South Asia, where intense monsoon rains have led to the destruction of agroforestry systems, particularly those located on sloping lands (Poudel *et al.,* 2023).

5.5. Climate Change Mitigation and Adaptation Potential of Agroforestry Systems

Despite the adverse impacts of climate change, agroforestry systems also offer opportunities for both mitigation and adaptation. Trees in agroforestry systems sequester carbon in both aboveground biomass and soils, helping to offset carbon emissions. Additionally, agroforestry can enhance the resilience of

agricultural systems by improving soil health, increasing biodiversity, and reducing the risk of soil erosion during extreme weather events. Recent studies emphasize the importance of adaptive management practices to strengthen the resilience of agroforestry systems to climate change. These include selecting climate-resilient tree species, diversifying species to reduce risks from pests and diseases, and incorporating soil conservation measures to protect against drought and flooding (Dhyani *et al.,* 2021). Agroforestry systems that integrate trees with deep root systems, such as *Faidherbia albida* and *Albizia lebbeck*, have been shown to improve water retention and provide ecosystem services even during periods of water scarcity.

Climate change poses significant challenges to agroforestry systems through rising temperatures, altered precipitation patterns, increased frequency of extreme weather events, and the spread of pests and diseases. However, agroforestry systems also provide vital mitigation and adaptation services that can help offset some of the impacts of climate change. Moving forward, targeted management strategies that incorporate climate-resilient species, water management techniques, and biodiversity conservation will be essential to enhancing the sustainability and resilience of agroforestry systems in the face of climate change.

6. Challenges and Opportunities

This review revealed the immense potential of agroforestry systems not only for supporting local livelihoods but also for climate change mitigation through enhanced carbon sequestration and delivery of ecosystem services. Despite the numerous benefits that agroforestry systems have to offer, there are still many challenges and barriers to its adoption by farmers. An analysis of global literature (Tranchina *et al.,* 2024), revealed five common issues encountered by stakeholders, viz., knowledge barriers, socio-economic issues, lack of time or labour for implementation or maintenance, need for upfront economic investment and technical support to implement or maintain agroforestry systems. In India, several studies have enumerated the challenges impeding the adoption of agroforestry which include lack of quality planting material, inadequate research for species selection and agroforestry models based on locality or agro-climatic zones, scarcity of market linkage and cumbersome legislation in respect of tree felling, wood transportation, processing (Sharma *et al.,* 2017). Limited access to markets for agroforestry products can discourage farmers from diversifying their production. Complex regulatory processes can deter farmers from adopting agroforestry practices. Further, many agroforestry practices are deeply entwined with the cultural practices of the communities which may influence species selection processes, and management. This may pose a difficulty in making new knowledge and innovations socially acceptable by the community who are used to traditional methods.

A comprehensive analysis of agroforestry systems from different agro-climatic regions of India indicated economic viability with an internal rate of return (IRR) ranging from 25 to 68 and a Benefit-Cost (B: C) ratio of 1.01 to 4.17 (Planning Commission, 2001). The alder-based shifting cultivation of Nagaland has been appraised as an outstanding model of sustainable land use through the application of traditional knowledge that has evolved for many generations (Das *et al.,* 2012; Rathore *et al.,* 2010). In a study on certain AFS of Assam, Yasmita-Ulman *et al.,* (2016; 2020; 2021) recommended that agroforestry systems harbour

rich floral, mammalian and avian diversity, and can be promoted as conservation models with some management interventions to curb hunting and unsustainable resource extraction, especially where pressure on natural forests is increasing. Therefore to fully realize this potential different measures can be implemented. Agroforestry practitioners can be encouraged to participate in carbon credit markets where they receive compensation for sequestering carbon through agroforestry practices. This can provide an additional revenue stream and incentivize sustainable practices. Reforestation and afforestation initiatives within agroforestry systems can increase carbon stocks and enhance ecosystem services, such as improved habitat for wildlife and reduced erosion. Traditional ecological knowledge of farmers can be enhanced by integration with scientific innovations in agroforestry technologies, such as improved seed varieties, soil and water management practices, sustainable harvesting, value-addition of produce and marketing strategies. This can be done by linking farmers with local agricultural extension services and enabling collaboration across multiple sectors including agriculture, forestry, environmental, industrial and commercial sectors to support long-term productivity, profitability and sustainability. Lastly, establishing social networks of agroforestry practitioners can facilitate knowledge sharing and support systems. Collaborative approaches involving local communities can enhance commitment to sustainable agroforestry initiatives leading to more effective implementation tailored to local needs.

7. Conclusion

The review study highlight that the agroforestry systems of the Indian Eastern Himalayas represent a harmonious integration of short-term economic and livelihood needs with long-term ecological sustainability. These systems, exemplified by the cardamom-based agroforestry practices, alder-based agroforestry practices and all other agroforestry systems significantly enhance the economic status of rural communities while promoting the conservation, restoration of mountain ecosystems and supporting all the ecosystems services including provisioning, regulating, supporting, and cultural benefits, thereby aligning with the Millennium Ecosystem Assessment (MA 2005) framework. Unlike modern plantation forests and monoculture systems, the indigenous practices underpinning these agroforestry systems are inherently adaptive and sustainable, offering vital services such as biodiversity conservation, hydrological balance maintenance, soil health improvement, and carbon sequestration. These contributions are crucial for the resilience and sustainability of both human and natural systems, benefiting upstream and downstream communities alike. To fully realize the potential of these systems, it is imperative to integrate traditional knowledge with scientific advancements, promote sustainable management practices, and leverage technologies such as remote sensing and ecosystem modelling for precise monitoring and planning. Additionally, effective policy frameworks that incentivize sustainable agroforestry practices, capacity-building initiatives to disseminate best practices, and robust valuation of ecosystem services are essential for their success. Multi-disciplinary research and collaborative efforts among governments, NGOs, research institutions, and local communities further underpin the scalability and sustainability of agroforestry systems. By addressing these priorities, agroforestry in the Indian Eastern Himalayas can emerge as a pivotal solution to global

environmental challenges, advancing carbon sequestration, ecosystem health, and the overall well-being of mountain communities.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*
Conceived and designed the research or analysis	Yes	No	Yes	No
Collected the data	Yes	Yes	Yes	Yes
Contributed to data analysis and interpretation	Yes	Yes	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	No	Yes	No
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